Evaluation and Applications of Cloud Climatologies from CALIOP

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ABSTRACT

Clouds have a major impact on the Earth radiation budget and differences in the representation of clouds in global climate models are responsible for much of the spread in predicted climate sensitivity. Existing cloud climatologies, against which these models can be tested, have many limitations. The CALIOP lidar, carried on the CALIPSO satellite, has now acquired over two years of nearly continuous cloud and aerosol observations. This dataset provides an improved basis for the characterization of 3-D global cloudiness. Global average cloud cover measured by CALIOP is about 75%, significantly higher than for existing cloud climatologies due to the sensitivity of CALIOP to optically thin cloud. Day/night biases in cloud detection appear to be small. This presentation will discuss detection sensitivity and other issues associated with producing a cloud climatology, characteristics of cloud cover statistics derived from CALIOP data, and applications of those statistics.

1. INTRODUCTION

CALIOP is a two-wavelength depolarization lidar carried on the CALIPSO satellite. CALIPSO was launched in April 2006 and has been acquiring global observations of clouds and aerosols since June 2006. CALIPSO flies as part of the A-train constellation, providing cloud and aerosol profiles which are spatially and temporally coincident with MODIS and CloudSat observations. Long-term global cloud climatologies have been derived from a number of different passive satellite sensors. The CALIPSO dataset provides an opportunity to evaluate these different climatologies. The first step is to evaluate climatologies of simple parameters such as cloud occurrence and so here we examine the performance of CALIOP in detecting cloud and show some example statistics.

2. CALIOP MEASUREMENTS

CALIOP operates at two wavelengths, 532 nm and 1064 nm. Details on the instrument design and performance are described in [1] and [2]. Detection of cloud (and aerosol) layers primarily relies on the 532 nm channel as it is more sensitive than the 1064 nm channel. Each profile is scanned from an altitude of 30-km to -1.5 km. All altitudes are referenced to the Earth's geoid, which roughly corresponds to mean sea level. Cloud and aerosol layers are detected using an adaptive threshold detection technique [3]. The threshold is applied to profiles of attenuated scattering ratio, computed using gridded pressure and temperature data from the GEOS-5 meteorological dataset, rather than to the backscatter signal itself. To avoid false positives, the threshold is altitude-dependent,as the SNR of clear-air returns at high altitudes is lower than at low altitudes. The threshold is computed as the sum of a constant value and a range-dependent value. The constant value is determined using the measured RMS variability of the signal at an altitude where the atmospheric return is negligible and is primarily due to the solar background. Thus, when CALIPSO flies over a broken cloud field during daytime the threshold is adjusted on each profile as necessary to avoid false positives due to increased signal noise. The range-dependent part of the threshold is computed to account for the increase in SNR as the signal penetrates deeper into the atmosphere and the clear-air backscatter signal increases.

The base of a layer can be identified as the point where the attenuated scattering ratio falls back to unity. However, if the layer attenuates the signal significantly, the attenuated scattering ratio will fall to less than unity in clear air below the layer. Therefore, two tests are used to identify cloud base: the attenuated scattering ratio must fall below unity for a certain number of successive range bins, and must also be constant for some minimum altitude range.

Backscatter returns from the tops of dense clouds are about three orders of magnitude larger than those from clear air. Thus, although dense clouds can be detected using individual laser shots, aerosols and weaker clouds can only be detected after a number of profiles are averaged together. To maximize the information retrieved from the data, the detection algorithm scans profiles for layers at several different horizontal resolutions. The first step in the layer detection process is to horizontally average the downlinked profiles to a horizontal resolution of 5 km. The layer detection algorithm is then applied to these 5-km profiles. Layers detected are identified and removed from the 5-km profiles. The data is then re-averaged to 20-km and scanned again. Weaker layers, which were not detectable at 5-km resolution, may be found. Any layers found at 20-km resolution are removed from the averaged profile. The data is then re-averaged to 80-km resolution and scanned again. Again, weak layers which were undetectable at 20-km may be found and reported at 80-km resolution. Layers found at 5-km, 20-km, and 80-km resolution are all reported in the 5-km cloud and aerosol layer product. If a layer is detected in a 5-km profile, then the profiles going into that 5-km profile are examined at 1-km resolution and at single shot resolution. Cloud layers found in 1-km and single-shot profiles are reported in the 1-km and 1/3-km cloud layer products, respectively, but not in the 5-km cloud layer product.

Once layer tops and bases have been located, a scene identification algorithm is applied to identify the layers as cloud or aerosol. If the lidar signal reaches the surface, the surface return is also identified as a layer. A surface classification algorithm is used to identify the surface so it is not classified as a cloud or aerosol layer. Cloud-aerosol discrimination (CAD) is based on comparing the observed 532 nm backscatter signal strength and the ratio of 532 nm and 1064 nm signals (the 'color ratio') with climatological probability distribution functions (PDFs) of these quantities. The CAD algorithm used to produce the Version 1 data product is described in [4]. The Version 1 algorithm was developed prior to launch and uses PDFs available at the time, primarily from the LITE and CPL instruments. For the Version 2 data product, the PDFs used by the CAD algorithm were recomputed from CALIOP data. The intention in the overall design of the Version 2 CAD algorithm is to be somewhat conservative in identifying aerosol layers, such that if there is ambiguity in the classification it favors identification as cloud to keep cloud artifacts out of the aerosol product.

3. DETECTION SENSITIVITY

As described above, single-shot profiles from CALIOP have low signal-to-noise ratio and averaging is necessary to detect aerosols and weaker clouds. Figure 1 illustrates the detection sensitivity of CALIOP. The four panels show histograms of the mean backscatter of cloud layers detected by the standard layer detection algorithm when averaging 15 or 240 laser shots (horizontal resolution of 5 km or 80 km). Results for daytime and nighttime are shown separately. It can be seen that the detection sensitivity increases significantly when the averaging increases from 15 to 240 shots.

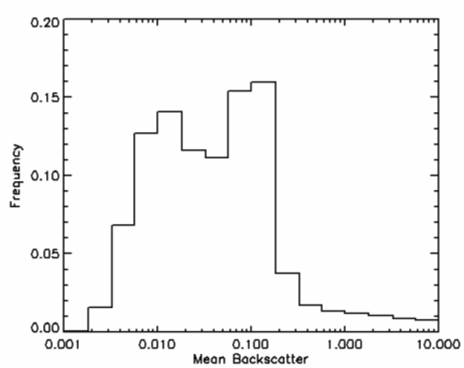
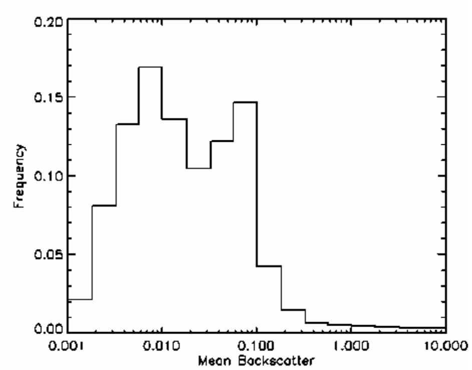
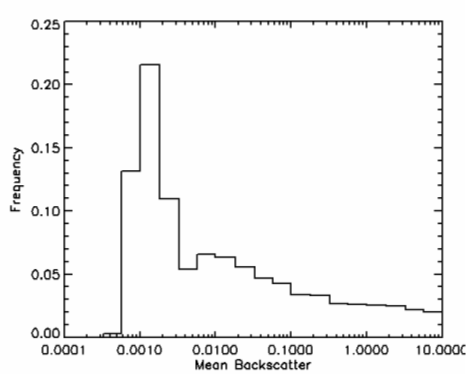
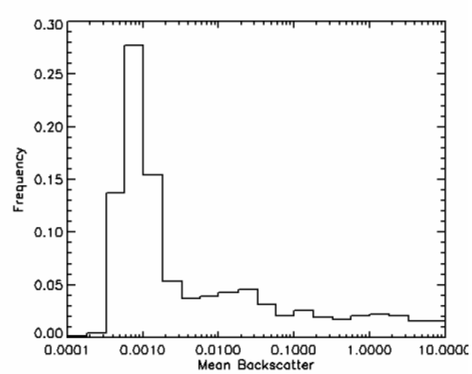
	Day	Night
5 km averaging		
80 km averaging		

Figure 1. Histogram of layer-average backscatter (/km /sr) for cloud layers found with 5-km and 80-km horizontal averaging. Statistics are for the period July 1-7, 2006.

Table 1 gives minimum thresholds, β_{min}, for detection at 532 nm, determined somewhat subjectively from the histograms in Figure 1. The difference in daytime and nighttime thresholds is small for 5-km averaging and about a factor of 2 for 80-km averaging. Table 1 also gives these backscatter thresholds as converted into equivalent optical depths, τ, assuming a cloud thickness of 1 km and a lidar ratio of 25. From these numbers, we can expect a day-night bias in CALIOP cloud statistics, but only for clouds with optical depths which are quite small compared to the detection limits of passive satellite sensors (typically about $\tau = 0.3$).

Table 1. CALIOP detection sensitivity

averaging interval	β_{min}(/km/sr) day/night	τ_{min} day/night
5 km	2E-3/3E-3	0.05/0.075
80 km	3E-4/6E-4	0.0075/0.015

The ability of CALIOP to sense low clouds and to measure cloud base is limited by the attenuation of the lidar signal. Figure 2 quantifies the extent of this effect, showing the cumulative distribution function of the lowest altitude reached before the lidar signal is completely attenuated for cloudy columns and for all columns (all-sky). About 61% of the lidar profiles reach the Earth surface and roughly 80% of the profiles reach the lowest kilometer of the atmosphere (solid line). The dashed line shows the probability of reaching altitude *z* for those columns where the signal is fully attenuated by cloud. These results are roughly consistent with those obtained from LITE.

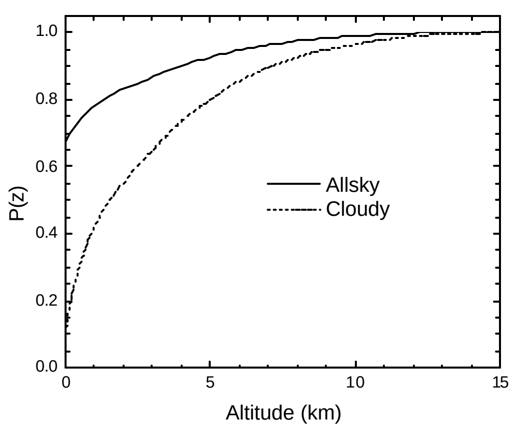


Figure 2. Penetration depth of CALIOP lidar signal.

Figure 3 shows profiles of cloud layer fraction from the surface to 8 km from CALIOP and from CloudSat. Differences are due to the combined effects of the greater sensitivity of CALIOP to thin cirrus, attenuation of the CALIOP signal in dense clouds, and limited sensitivity of CloudSat near the ground and to liquid water clouds with small droplet sizes. In the mid-troposphere, CloudSat measures higher cloud fraction than CALIOP, probably because of attenuation of the CALIOP signal by higher, dense cloud.

Near the surface, however, CALIOP gives a cloud fraction nearly as large as CloudSat, with the peak in cloud occurrence closer to the surface. CloudSat suffers from reduced sensitivity to clouds near the surface due to effects from the finite length of the radar pulse and also due to the small droplet size of some boundary layer clouds. CALIOP suffers from neither of these problems and easily sees low clouds, as long as they are not located under optically thick clouds.

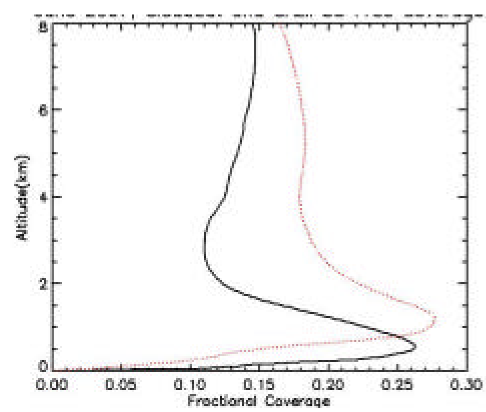


Figure 3. Vertically resolved cloud fraction from CALIOP (solid, black) and from CloudSat (dashed, red) (June 2007, global, day and night)

4. RESULTS

Table 2 shows average cloud cover derived from the CALIOP 5-km cloud layer product compared with results from global surface observations [5] and from the International Satellite Cloud Climatology Project (ISCCP) [6]. For CALIOP and ISCCP, day and night statistics are shown separately whereas day and night observations are combined for the surface observers. Cloud cover observed by CALIOP is significantly higher than from either ISCCP or surface observations, due at least in part to the greater sensitivity of CALIOP to optically thin cloud. Differences are greater over land than over ocean.

It is well known that the viewing geometry of passive satellites and surface observers causes the Earth-cover, which is what CALIPSO observes, to be somewhat overestimated [5]. Corrected for viewing geometry, the differences between CALIPSO cloud cover and the other estimates would be even larger.

Table 2. Cloud fraction from three observing systems

		CALIOP	ISCCP	Sfc Obs
Global	Night	0.735	0.606	0.610
	Day	0.790	0.625	
Land	Night	0.599	0.463	0.524
	Day	0.704	0.559	
Ocean	Night	0.819	0.676	0.648
	Day	0.833	0.661	

Notice also that over land both CALIOP and ISCCP show greater cloud cover during daytime than nighttime. CALIOP and ISCCP show opposite diurnal differences over ocean, but the magnitude of the diurnal difference is much smaller than over land. If there is a diurnal bias in CALIOP cloud cover due to reduced daytime sensitivity, it is not evident in these total-column statistics.

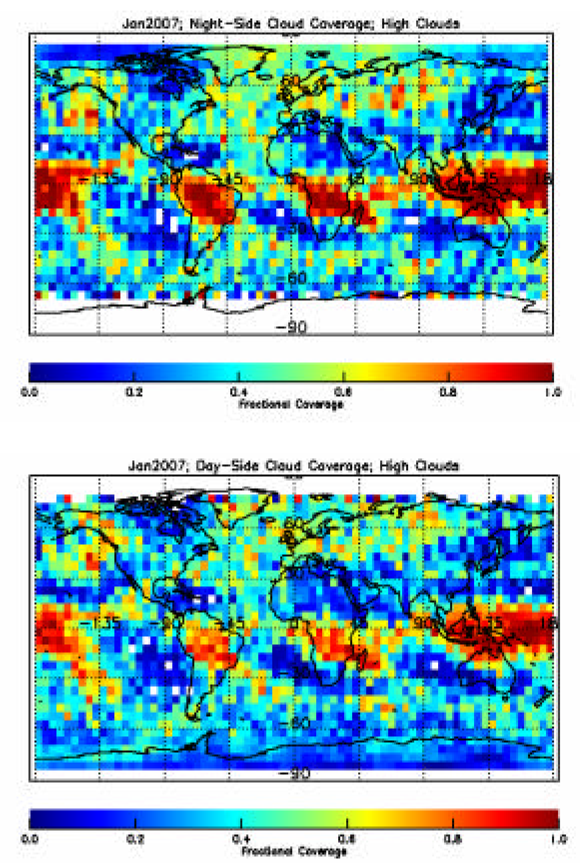


Figure 3. Mean cloud fraction of cloud with tops above 6.5 km for January 2007 (5^o x 5^o grid cells). Upper panel: nighttime; lower panel: daytime.

Figure 3 maps the fractional coverage of high clouds for the month of January 2007. The global mean fraction of high cloud shows very little day/night difference. Although the daytime and nighttime maps show similar geographic patterns of high cloud, more high cloud is observed at night in regions of tropical deep convection. This is consistent with our understanding of the diurnal cycle of tropical deep convection. From this and the sensitivity results in Section 3, the diurnal variation seen in these regions appears to be real and not a measurement bias.

5. SUMMARY

CALIOP observations are proving to be a useful complement to cloud observations from CloudSat and other A-train sensors. Development of rigorous cloud climatologies from CALIOP data is underway. Results will be made available in the future as a CALIPSO Level 3 product. Comparisons with other cloud climatologies will continue. Because CALIOP is more sensitive to optically thin cloud than either surface observers or passive satellite sensors, computing CALIOP cloud cover as a function of threshold cloud optical depth may provide a more meaningful comparison with other climatologies. This is part of ongoing activities and will be reported on in the future.

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